

THE VENTURI FLUME

By V. M. CONE,

*Irrigation Engineer, Office of Public Roads and Rural Engineering, United States
Department of Agriculture*

INTRODUCTION

Many devices have been developed for the measurement of water under field conditions—for example, in its delivery to irrigators. Nearly all of these devices employ the principles of either the weir or the orifice and, though each device is adapted to use in certain localities, probably none works satisfactorily under a great variety of field conditions. The ideal measuring device would (1) be inexpensive to construct, (2) be simple to operate, (3) require little maintenance, (4) be free from working parts, (5) be accurate in its measurement, (6) be free from sand, silt, or floating-trash troubles, and (7) require but little loss of head in the ditch. Such a panacea for all measurement-of-water ills does not seem probable, but progress is undoubtedly being made toward that end. The type of flume tested in the experiments on which this report is based possesses many of the qualities enumerated and may prove to be a satisfactory measuring device under general field conditions.

The purpose of this article is to present the fundamental plans and results of preliminary experiments on a new type of device, called the "Venturi flume," for measuring water in open channels, in order that those in practical need of such a device may know of its existence. Furthermore, it is hoped that the construction of larger sizes of Venturi flumes than were tested in the laboratory will be encouraged thereby and that they can be calibrated. It is not probable that the last word has been said on the design of the Venturi flume, for, although it has considerable promise, changes in details may prove to be necessary. The laboratory and field tests made thus far have failed to develop any serious inherent defects in the device.

Experiments made in the hydraulic laboratory at Fort Collins, Colorado, on measuring devices led to the development of the so-called Venturi flume during the season of 1915. It consists essentially of a flume with a converging and a diverging section and short "throat" section between them. The floor, which is level, is placed at the elevation of the bottom of the channel in which it is set. After many experiments had been made with different forms and shapes, the designs shown in figures 1, 6, 7, and 11 were adopted as most nearly meeting practical requirements. Venturi flumes with rectangular and trapezoidal cross sections (fig. 1, 6) no doubt will be the most used, but the other types (fig. 7, 11) were designed to meet special conditions where small flows must be measured.

The action of this device depends upon an adaptation or extension of Venturi's principle to the flow of a liquid in an open channel. As water passes through the flume there is a slight surface slope in the converging section, a rather sudden depression in the "throat" section, and a rise in the diverging section. The actual loss of head is small. The determination of the flow depends upon the velocity and wetted cross-sectional area at two points in the flume, and two gage readings, therefore, are necessary. One gage has been arbitrarily located upstream from the throat a distance equal to two-thirds the length of the converging section, to avoid possible influence due to contraction currents nearer the entrance to the flume; and the other gage has been located at the middle of the throat section, in order to obtain the greatest possible difference in elevation of water surface. The zero of these gages must be at the elevation of the floor of the flume, and it is especially important that the zero of the gages be at exactly the same elevation. The difference in heads, H_d , is a more important factor in determining the discharge than the depth of water in the channel, H_a or H_b .

Still boxes, or gage wells, are necessary for accurate readings of the water levels, because of the comparatively high velocity of the water flowing through the structure. Field tests on small Venturi flumes¹ indicated that readings taken to the nearest 0.01 foot on staff gages placed at the proper locations inside the flume, with the face of the gages countersunk flush with the surface of the side of the flume, would give an accuracy of measurement sufficient for general purposes. This would overcome the necessity for using gage wells, but recent tests made in the laboratory show that such staff-gage readings do not agree with readings taken in the gage wells when there is enough fall in the carrying channel to give a high velocity of flow through the flume, in which case H_d is a considerable amount. Until more is known of the accuracy of gages under different arrangements, caution should be used.

Instrument makers are at work on an automatic register to make graphs of the water elevations at the two gages, both records to appear on a single sheet. An integrating register would be most desirable, but the complexity of the law of flow through the flume certainly would require a complicated instrument.

The effect of the velocity of approach is automatically cared for in the device, and the formula takes account of the velocity of the water at each gage. The experiments indicate that the Venturi flume will be free from interference due to changes in the canal section, such as occur often from sand or silt accumulations or aquatic growths. Such obstructions make the use of the ordinary rating flume very troublesome, if not quite impossible, but these obstructions result only in changing the relative gage readings of the Venturi flume without altering the calibration of

¹ Tests made on the North Platte Project, United States Reclamation Service, Mitchell, Nebraska, under the general direction of Mr. Andrew Weiss, Project Manager.

the device. Since the velocity increases throughout the converging section, all material carried into the flume also will be carried out, and this self-cleaning feature is of considerable practical importance. When the depth of water is low, floating trash might lodge in the throat of the V-notch Venturi flume, which is of small cross section, but it would cause an accumulation of water in the upstream channel until the wetted cross section at the throat would be sufficient to allow the obstruction to pass. It must be borne in mind that a Venturi flume of whatever form must not be placed below canal grade, for this would give a standing-water condition which would alter the calibration of the device, and it would also allow sand and silt to accumulate within the structure at low velocities. It is important also that the width of the channel of approach be not greatly in excess of the greatest width of the flume, as this permits a silt bank to be deposited at either side wing of the flume.

A desirable phase of this device is the practical connection which it may make with the ditch banks. At the ends of the structure, wings may be placed at an angle of 90° to the axis of the structure to make the connection with the ditch banks, or the ends of the structure may be joined directly to the ditch lining.

Another practical feature in connection with the Venturi flume is the small loss of head required for purposes of measuring the flow. Table I shows for the V-notch flume the lost head for the different discharges obtained with different depths of water. The head at the upstream gage is called H_a , the head at the throat gage is called H_b , and the difference between these heads ($H_a - H_b$) is called H_d . Under usual conditions of operation the lost head will be negligible.

TABLE I.—Loss in head (in feet) in V-notch Venturi flume for different heads at the two gages

H_a	$H_d=0.05$		$H_d=0.10$		$H_d=0.15$		$H_d=0.20$		$H_d=0.25$		$H_d=0.30$	
	Q in second-feet.	Loss in head in feet.	Q in second-feet.	Loss in head in feet.	Q in second-feet.	Loss in head in feet.	Q in second-feet.	Loss in head in feet.	Q in second-feet.	Loss in head in feet.	Q in second-feet.	Loss in head in feet.
0.4.....	0.10	0.06	0.11	0.08	.....	.....	.....	.....	.....	.....	.....	.....
.6.....	.26	.05	.30	.07	.....	.....	.....	.....	.....	.....	.....	.....
.8.....	.49	.04	.60	.06	0.62	0.15	.....	.....	.....	.....	.....	.....
1.0.....	.81	.03	1.00	.06	1.09	.13	1.12	0.24	.....	.....	.....	.....
1.2.....	1.20	.03	1.52	.06	1.63	.11	1.76	.17	1.79	0.29	.....	.....
1.4.....	1.71	.03	2.17	.05	2.42	.10	2.56	.14	2.63	.21	2.67	0.31
1.6.....	2.33	.03	2.96	.05	3.31	.09	3.52	.12	3.65	.17	3.74	.23

RECTANGULAR VENTURI FLUME

The original idea was to invent a device which would replace the ordinary rating flume, such as is used in irrigation canals. It was thought that the flume might be converted into a self-contained measuring device by placing a restricted section in the flume, which would cause a loss of

head, and a determination of such loss of head would indicate the volume of water flowing in the channel. Thus far, Venturi's principle had not been considered in the action of such a device. Small flumes with vertical sides were used in the preliminary experiments; and, after employing several different ratios of widths of throat to lengths of flume, lengths

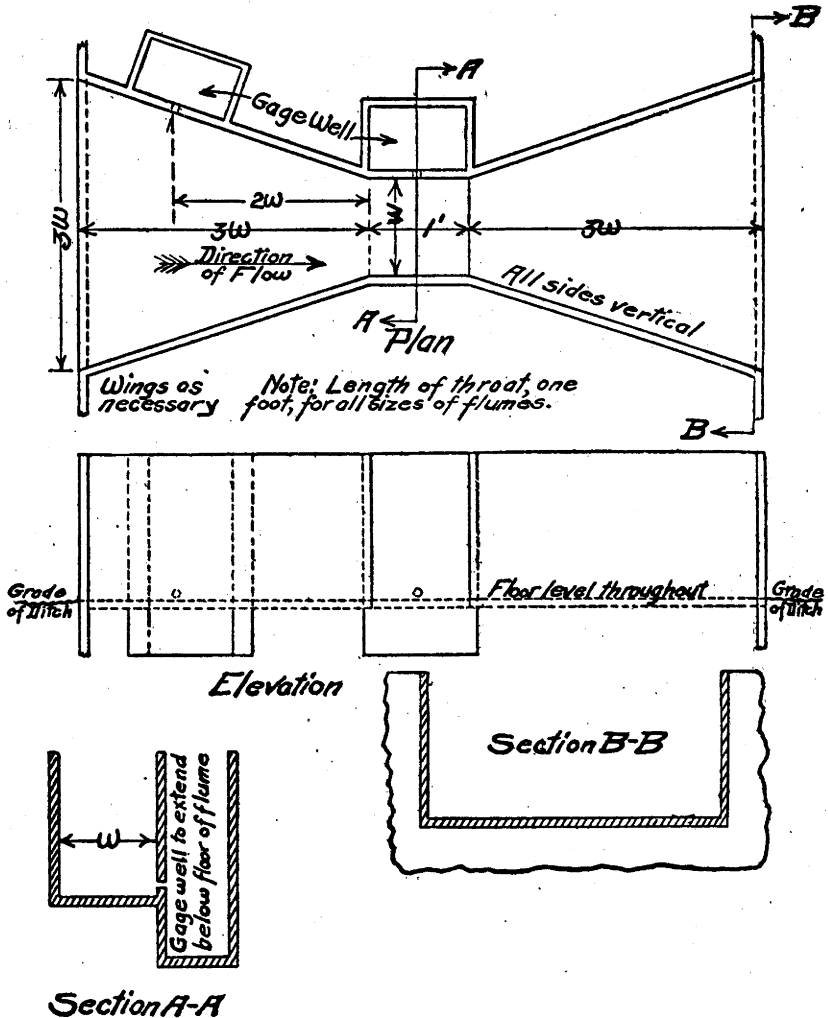


FIG. 1.—Standard plans for the Venturi flume with rectangular cross section.

of throat, and arrangements of gages and end wings, the form shown in figure 1 was chosen as the standard. A greater length of converging and diverging section and a rounding of the throat section would result in less loss of head and greater accuracy in measurement of flow, but the standard was chosen as a compromise between accuracy and cost.

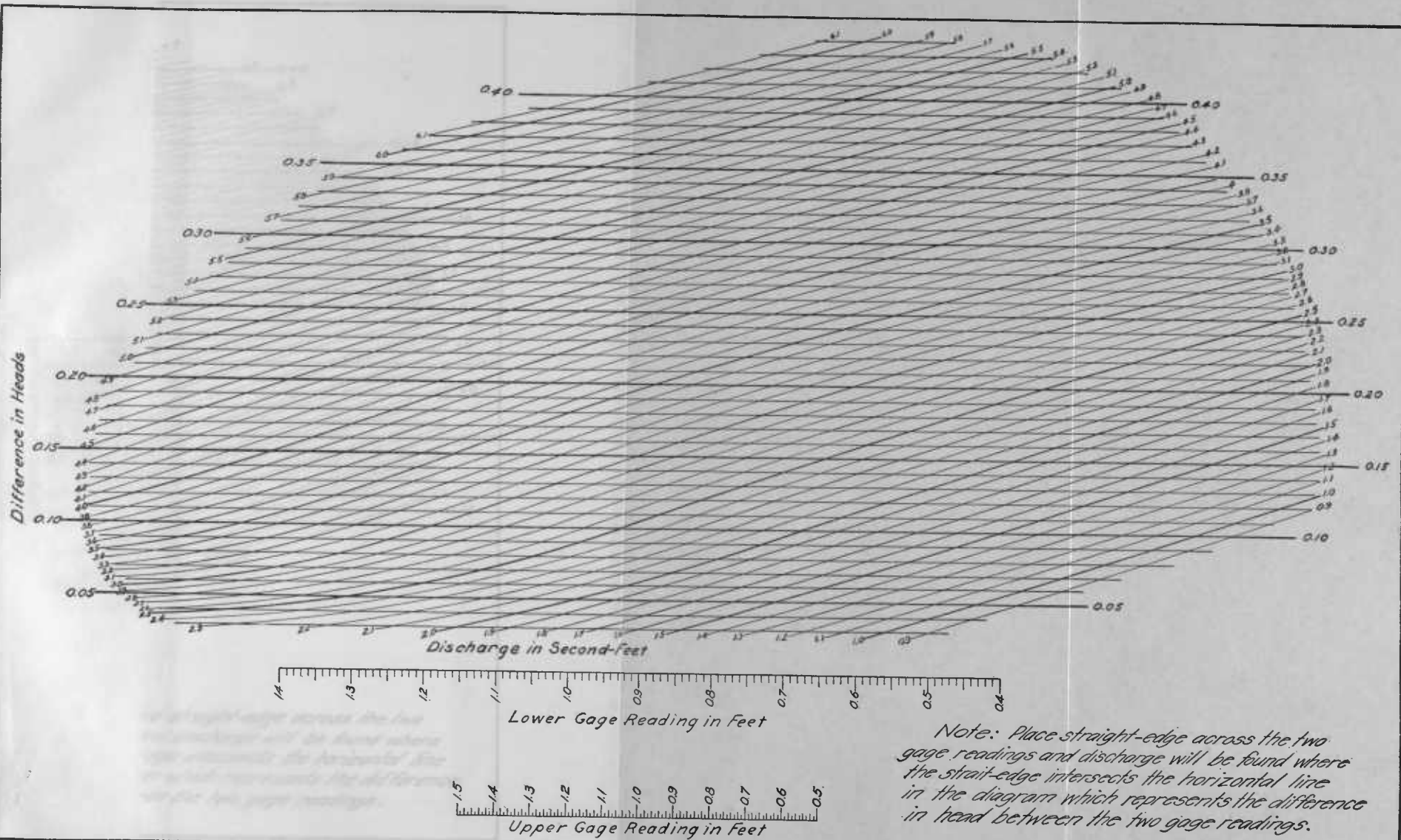
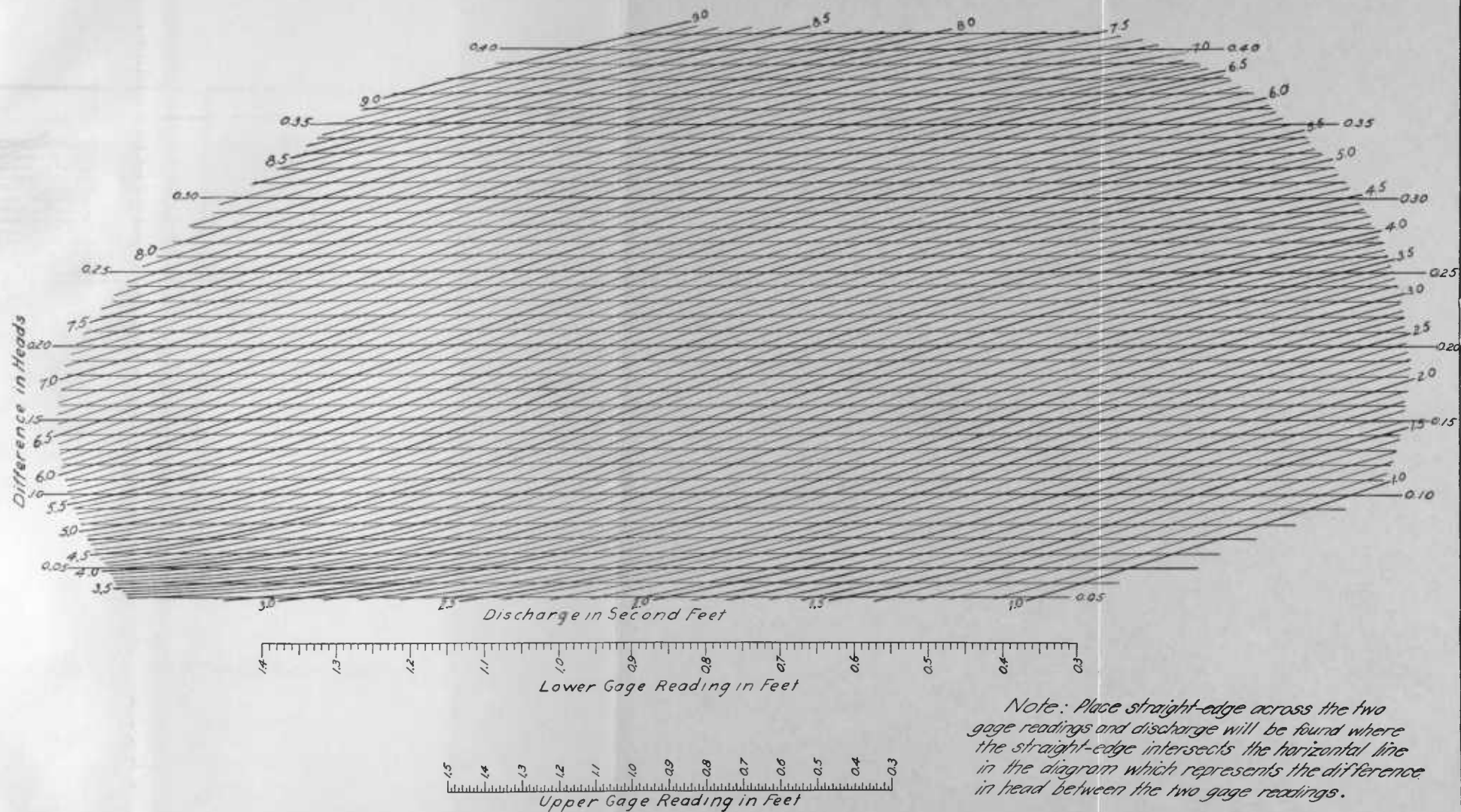


FIG. 2.—Discharge curves for the rectangular Venturi flume with 1-foot throat.



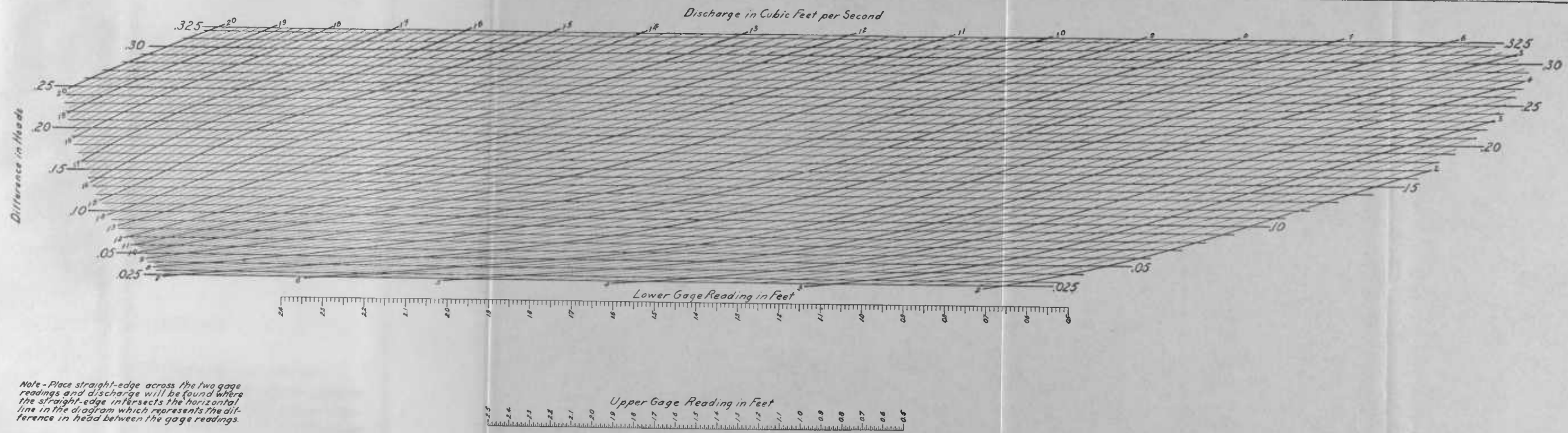
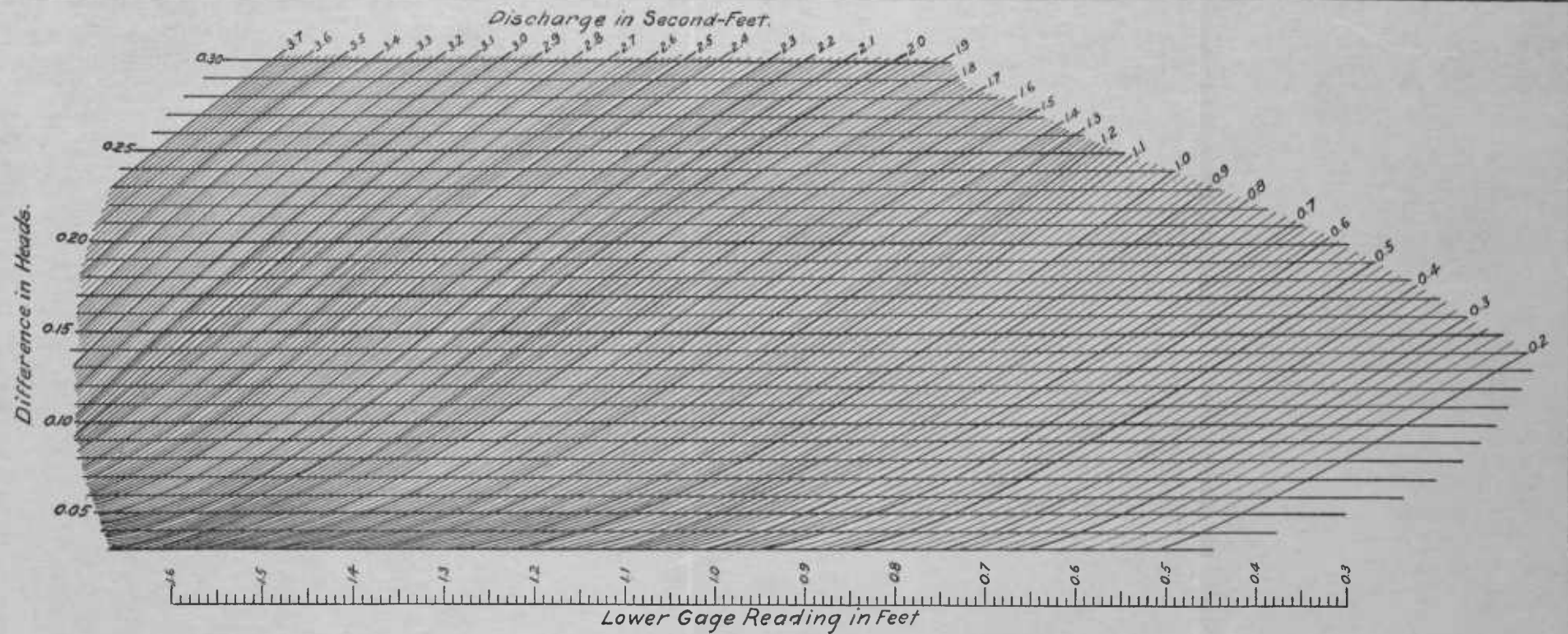
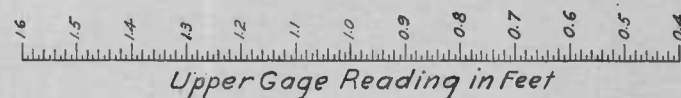


FIG. 4.—Discharge curves for the rectangular Venturi flume with 2-foot throat.



Note: Place straight-edge across the two gage readings and discharge will be found where the straight-edge intersects the horizontal line in the diagram which represents the difference in head between the two gage readings.



The Venturi flume with rectangular cross section is especially simple to build of any material suitable for use in water, and will probably be the most popular type. Its practical minimum throat width is 1 foot, and the largest one thus far constructed has a throat width of 7 feet.

A general formula for the discharge through rectangular Venturi flumes has not been worked out, because calibrations have not been made on flumes large enough to warrant a formula of general application. Discharge curves are given in figures 2, 3, and 4 for throat widths of 1, $1\frac{1}{2}$, and 2 feet.

TRAPEZOIDAL VENTURI FLUME WITH SIDE SLOPES OF $1\frac{1}{2}$ TO 1

Although no trapezoidal Venturi flumes with side slopes of $1\frac{1}{2}$ to 1 have been constructed, there is no reason apparent why their behavior would not be similar to that of rectangular cross-sectional type. The side slopes of $1\frac{1}{2}$ to 1 will fit the majority of canal banks, and the resulting cross section will accommodate a greater range of discharges than the rectangular flumes. Therefore it is believed that, for the larger canals, the more satisfactory type of Venturi flume will have a trapezoidal cross section with side slopes of $1\frac{1}{2}$ to 1. It will fit nicely with concrete lining of canals. This form does not call for warped surfaces, because the slopes are taken normal to the axial line of the flume, which is in a plane normal to the side of the throat section but is not normal to the side of the converging and diverging sections. The general plans for this type are given in figure 6, but no discharge curves are available at this time. It is expected that calibrations will be made from structures as they are installed under actual field conditions.

V-NOTCH VENTURI FLUME

There has been a demand for many years for a device to measure small flows of water where the permissible loss of head is small, or where sand and silt is carried by the water. After repeated unsuccessful attempts had been made to arrange a modification of an orifice or weir to meet these conditions, it was decided to ascertain what combination could be made of the Venturi flume and the triangular-notch weir. The result was the V-notch Venturi flume shown in figures 7 and 8. The side slopes of $\frac{1}{2}$ to 1, in a plane normal to the axis of the flume, give a cross-sectional area of the throat section for different depths of water, which allows a good range of discharge from extreme high to low heads. This form is applicable under conditions of head commonly found in small ditches to flows of from 0.1 to 2 or 3 second-feet.

Discharges through V-notch Venturi flumes are given in graphic form in figure 5, and those computed from the formula are given in Table II.

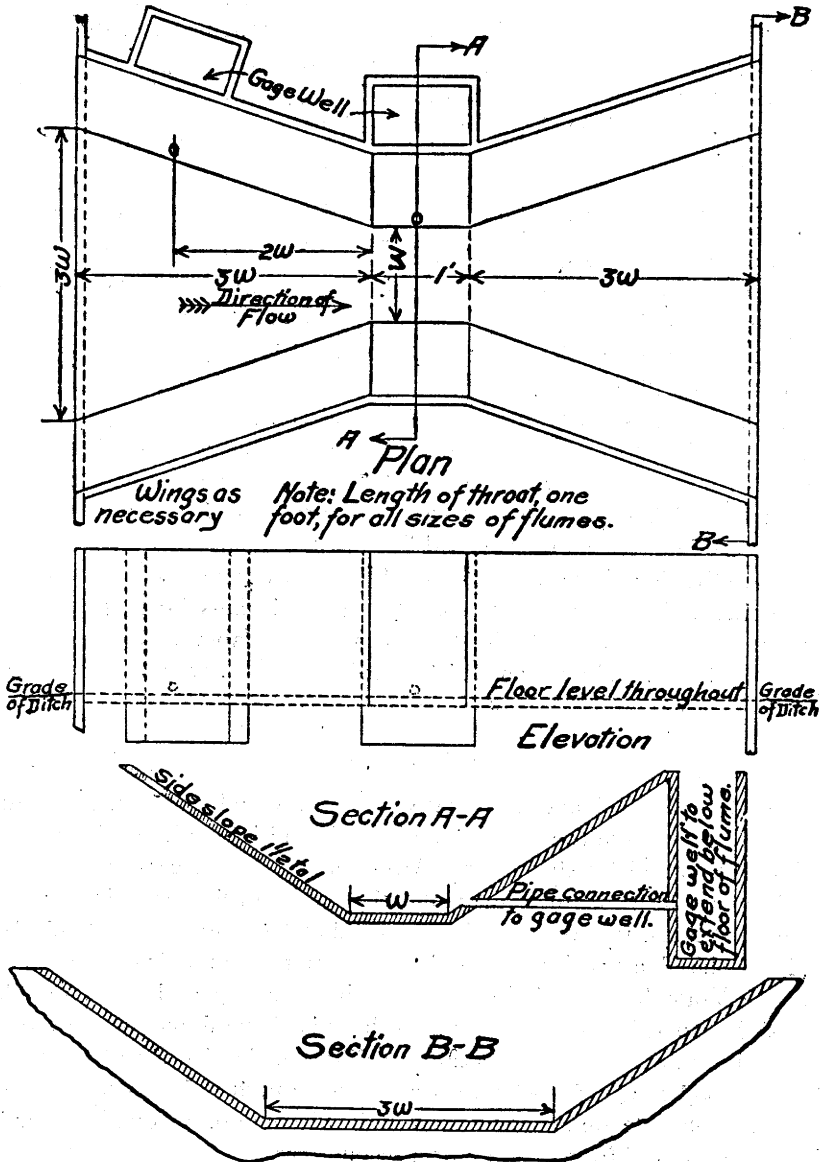


FIG. 6.—Standard plans for the Venturi flume with trapezoidal cross section.

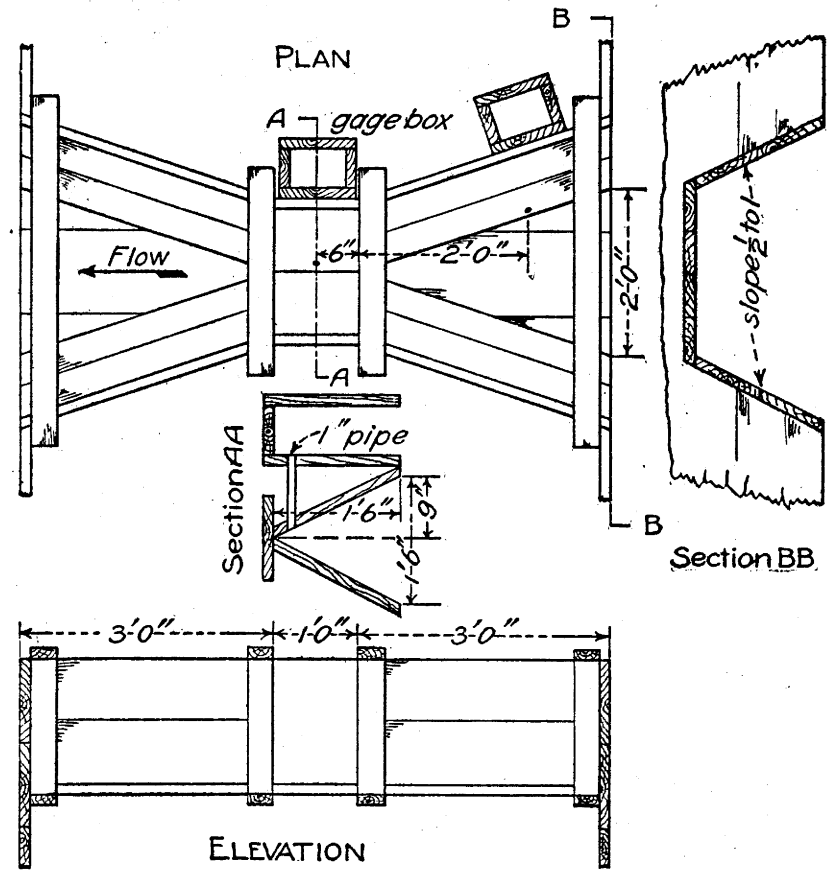


FIG. 7.—Plan, elevation, and sections of the V-notch Venturi flume.

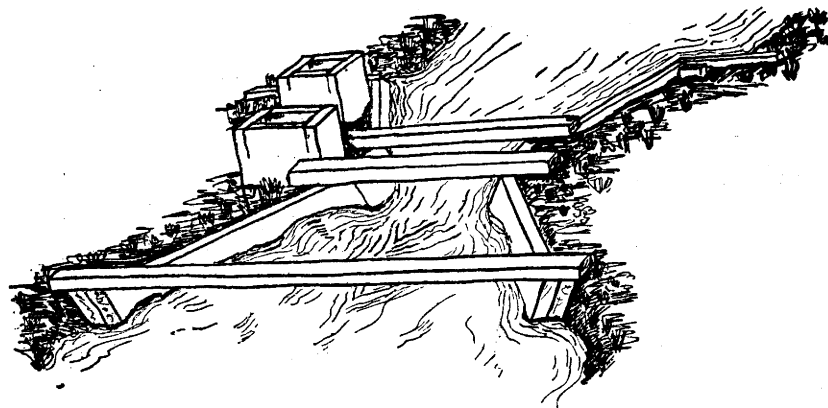


FIG. 8.—Sketch of the Venturi flume, showing installation in ditch.

The effect upon the discharge caused by different arrangements of the channels of approach and recession is shown by the following experimental results. The discharges for each condition have been compared with those for the standard arrangement.

Extending the converging section to a length of approximately 6 feet instead of 3 feet, as in the standard plan (fig. 7), but with the same angle of convergence, caused a decrease in discharge of not to exceed 0.5 per cent for any depth of water.

A channel of approach with parallel sides, having a side slope of $\frac{1}{2}$ to 1 and a bottom width of 2 feet, joined to the upstream end of the Venturi flume caused a decrease in discharge of less than 1 per cent for any depth of water. This change was comparable to eliminating the 90° wings at the upstream end and joining the device directly to the lined section of a ditch.

With the standard construction for the upstream portion of the flume, a channel of recession similar to the previously described channel of approach was provided. This change had no appreciable effect upon the discharge for any depth of water.

A piece of 2- by 4-inch timber was placed on edge at the upstream end of the flume and nailed to the floor. Its position was normal to the axis of the flume, and it extended across the full width of the section. The increase in discharge due to this change did not exceed 1 per cent for any depth of water.

DERIVATION OF FORMULA FOR DISCHARGE THROUGH THE V-NOTCH VENTURI FLUME

From Bernoulli's theorem:

$$\frac{V_a^2}{2g} + p + H_a = \frac{V_b^2}{2g} + p + H_b \quad (1)$$

in which V_a and H_a represent the velocity and head at the gage in the upstream section and V_b and H_b represent the velocity and head in the throat section.

$$\text{from (1)} \quad V_b^2 = V_a^2 + 2gH_a \quad (2)$$

where $H_a = H_a - H_b$

$$Q = A_a V_a = A_b V_b$$

$$V_a = \frac{A_b V_b}{A_a} = \frac{\frac{H_b^2 V_b}{2}}{(2\frac{2}{3} + H_a) \frac{H_a}{2}} \quad (3)$$

substituting (3) in (2)

$$V_b^2 = \frac{H_b^4 V_b^2}{(2\frac{2}{3} + H_a)^2 H_a^2} + 2gH_a$$

$$V_b = \sqrt{\frac{2gH_a}{1 - \frac{H_b^4}{(2\frac{2}{3} + H_a)^2 H_a^2}}}$$

and

$$Q = V_b A_b = \frac{H_b^2}{2} \sqrt{\frac{2gH_a}{1 - \frac{H_b^4}{(2\frac{2}{3} + H_a)^2 H_a^2}}} \quad (4)$$

As shown in Table III, discharge values computed by equation (4) are higher than those obtained by experiment, because the equation does not contain a correction factor for the effect of contraction and friction. Table III and figure 9, plotted from this table, show the correction factor (C) to be greater for high and low values of H_a than for medium values of H_a , and (C) increases as H_a increases. To avoid confusion, coefficients (C) for H_a 's of 1.6 feet, 1 foot, and 0.4 foot, only, have been plotted in figure 9. The assumed limiting curves are shown in dotted

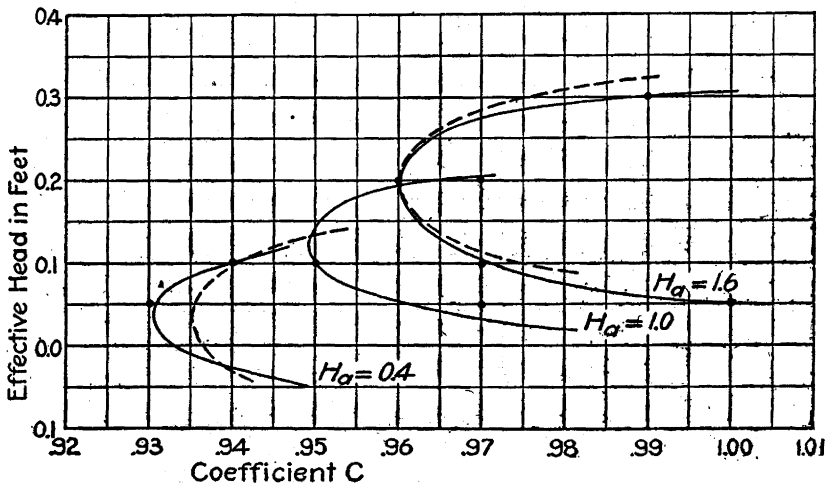


FIG. 9.—Plot of values of coefficient C for V-notch Venturi flume.

lines. The curves for the intermediate heads were assumed to have a straight line variation between the extreme curves and to change only in position.

The equation of the upper limiting curve, $H_a = 1.6$ feet, referred to the point 0.96, 0.2 as the origin, is of the form

$$y^n = ax$$

substituting values to find n and a ,

$0.1^n = 0.0167a$	$n = \frac{\log 11.13}{\log 3.33}$
$0.03^n = 0.0015a$	$n = 2.00$
$\frac{0.1^n}{0.03^n} = \frac{0.0167a}{0.0015a}$	$(0.1)^2 = 0.0167a$
$3.33^n = 11.13$	$a = \frac{0.01}{0.0167} = 0.6$
$n \log 3.33 = \log 11.13$	

The equation is therefore $y^2 = 0.6x$. With the origin moved to the point o, o , the equation of the upper limiting parabola becomes

$$(y - 0.2)^2 = 0.6(x - 0.96) \quad (5)$$

and similarly the equation for the lower limiting curve, H_a , approxi-

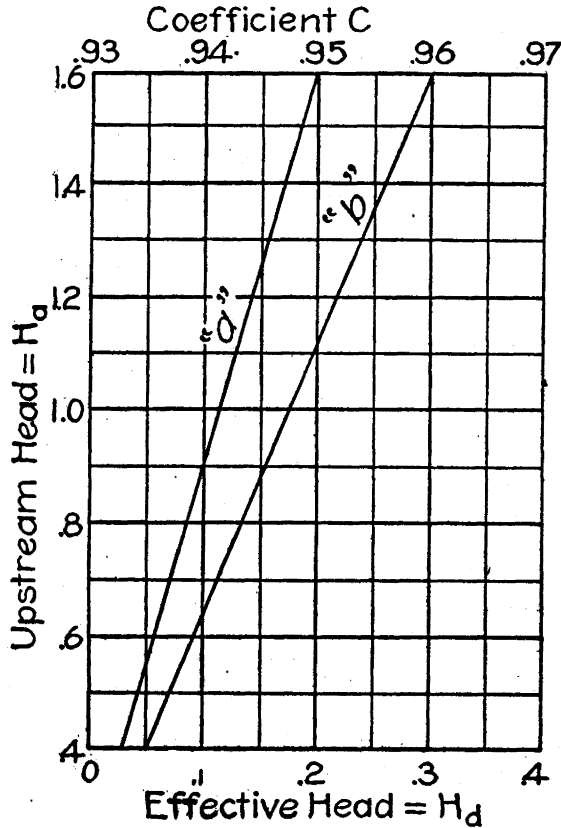


FIG. 10.—Plot of constants for curves shown in figure 9.

mately 0.4 foot, is found to be

$$(y - 0.03)^2 = 0.6(x - 0.935) \quad (6)$$

The constants for each curve were assumed to take a straight line variation, as shown in figure 10, in which the a line is for the constants with y , and the b line is for the constants with x .

By proportion from figure 10 and the substitution H_a for y ,

$$a = 0.14y - 0.02$$

or

$$a = 0.14H_a - 0.02$$

and

$$b = 0.02H_a + 0.93$$

Substituting these values in equation (5) or (6) gives

$$(y - 0.14H_a + 0.02)^2 = 0.6(x - 0.02H_a - 0.93)$$

but since $y = H_d$ and $x = c$,

$$(H_d - 0.14H_a + 0.02)^2 = 0.6(c - 0.02H_a - 0.93)$$

whence

$$C = \frac{(H_d - 0.14H_a + 0.02)^2 + 0.01H_a + 0.56}{0.6}$$

After the combination of the value of the coefficient C with the theoretical formula, equation (4) becomes

$$Q = \left[\frac{(H_d - 0.14H_a + 0.02)^2 + 0.01H_a + 0.56}{0.6} \right] \frac{H_b^2}{2} \sqrt{\frac{29H_d}{1 - \frac{H_b^4}{(2\frac{2}{3} + H_a)^2 H_a^2}}} \quad (7)$$

in which the bracketed portion represents the coefficient for contraction and friction, $\frac{H_b^2}{2}$ represents the wetted cross section of the throat of the flume, and the radical expression represents the velocity of flow.

Simplifying the above equation gives

$$Q = 6.68H_b^2[(H_d - 0.14H_a + 0.02)^2 + 0.01H_a + 0.56] \sqrt{\frac{H_d}{1 - \frac{H_b^4}{(2\frac{2}{3} + H_a)^2 H_a^2}}} \quad (8)$$

which is the discharge formula for the V-notch Venturi flume. Table II has been computed for this equation. The experimental discharge values are shown in curve form in figure 5.

Discharge values computed from equation (8), for any given H_a , increase as H_d is increased up to a certain point; but with further increase of H_d the discharge values decrease. At first thought this seems to be impossible; but it must be true, because in the limiting case where $H_d = H_a$, H_b becomes zero, and from the formula, Q must equal zero. Discharge values computed from equation (8) must plot into smoothly continuous curves of a reversed character, and these values must therefore ultimately decrease. From equation (7) it is evident that the wetted cross-sectional area of the throat varies as the square of the head, H_b , while the velocity varies nearly as the square root of the difference in head, H_d , and therefore for any given H_a , as the H_d increases the area decreases more rapidly than the velocity increases.

The calibration experiments with the V-notch Venturi flume did not show any decrease in discharge, such as mentioned above. For each H_a there is a definite limit to the value of the H_d which may be obtained

in the practical operation of this device, and it is probable that this limit is about at the reversing point on the discharge curves made from the formula. It was found by experiment that for any given H_a after a certain H_b had been obtained, a further lowering of the water surface in the diverging section had no influence upon the elevation of the water at the throat gage, H_b .

TABLE III.—Comparison of theoretical and experimental discharge values of V-notch Venturi flume

H_a	H_b	H_d	Q		C
			Experimental.	Computed. ^a	
0.4.....	0.35	0.05	0.102	0.110	0.93
.4.....	.30	.10	.107	.114	.94
1.0.....	.95	.05	.805	.832	.97
1.0.....	.90	.10	.999	1.052	.95
1.0.....	.80	.20	1.124	1.165	.97
1.6.....	1.55	.05	2.300	2.302	1.00
1.6.....	1.50	.10	2.925	3.023	.97
1.6.....	1.40	.20	3.525	3.669	.96
1.6.....	1.30	.30	3.802	3.830	.99

^a Discharges computed by equation (4), p. 122.

TRAPEZOIDAL VENTURI FLUME WITH SIDE SLOPES OF 1 TO 1

This is a special type which was developed to meet a condition common in some sections of the irrigated West, where a ditch is used to carry a small head of water for orchard irrigation at one time and a flow of approximately 10 second-feet for alfalfa irrigation at another time. This requires a quite flexible measuring device, and therefore called for the design shown in figure 11. The side slopes for this type of Venturi flume are 1 to 1, and it is expected that it will be built only in the one size; that is, with a 6-inch bottom throat width. The discharges through this Venturi flume are given in graphic form in figure 12.

The discharge through the Venturi flume with trapezoidal cross section, having side slopes of 1 to 1 in a plane normal to the axis of the flume and with a bottom throat width of 6 inches, is represented by the following equation, which was derived in a manner similar to that given for the V-notch Venturi flume:

$$Q = \left[\frac{[(H_a - 0.09 H_a - 0.005)^2 + 0.001 H_a + 0.274]}{0.30} \right] \left(\frac{1}{2} + H_b \right) H_b \sqrt{1 - \frac{29 H_a}{\left(\frac{1}{2} + H_b \right)^2 H_b^2} \left(\frac{11}{6} + H_a \right) H_a^2}$$

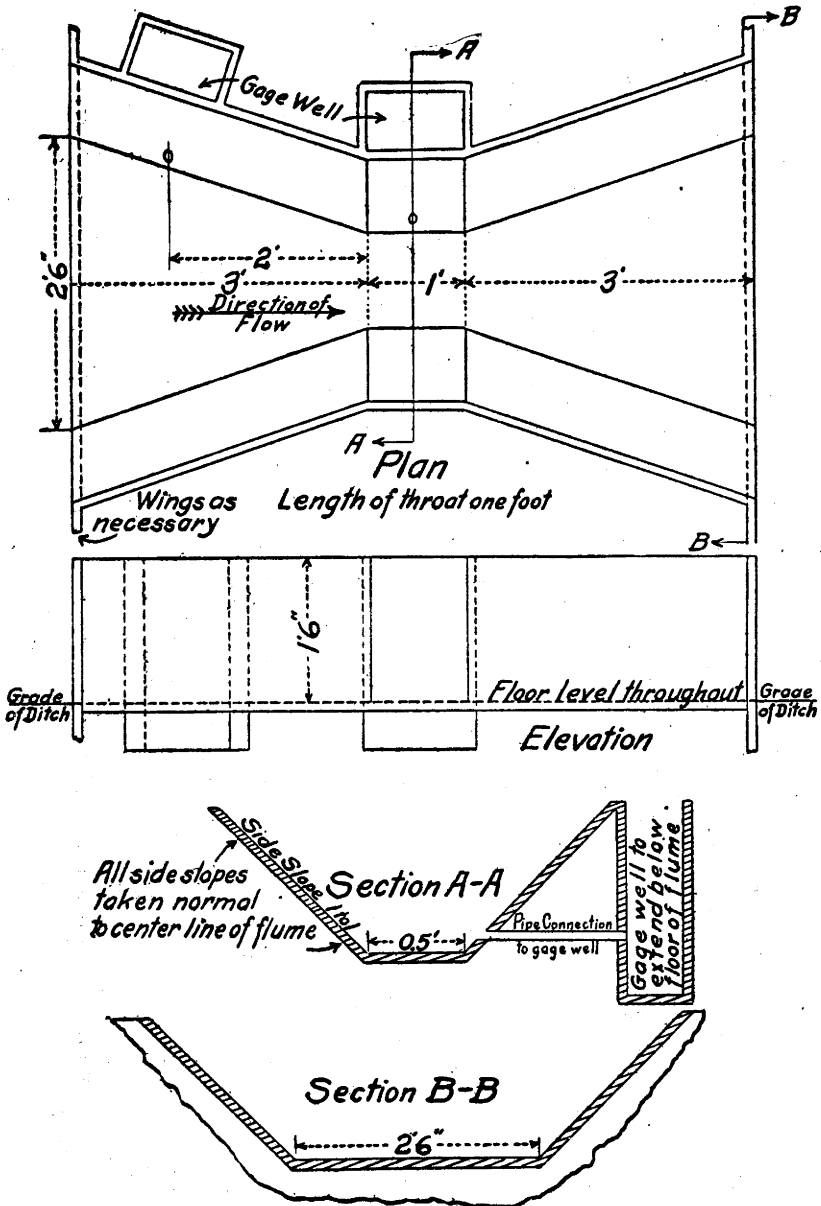


FIG. 11.—Plan for the trapezoidal Venturi flume with 0.5 foot bottom width, side slopes 1 to 1.

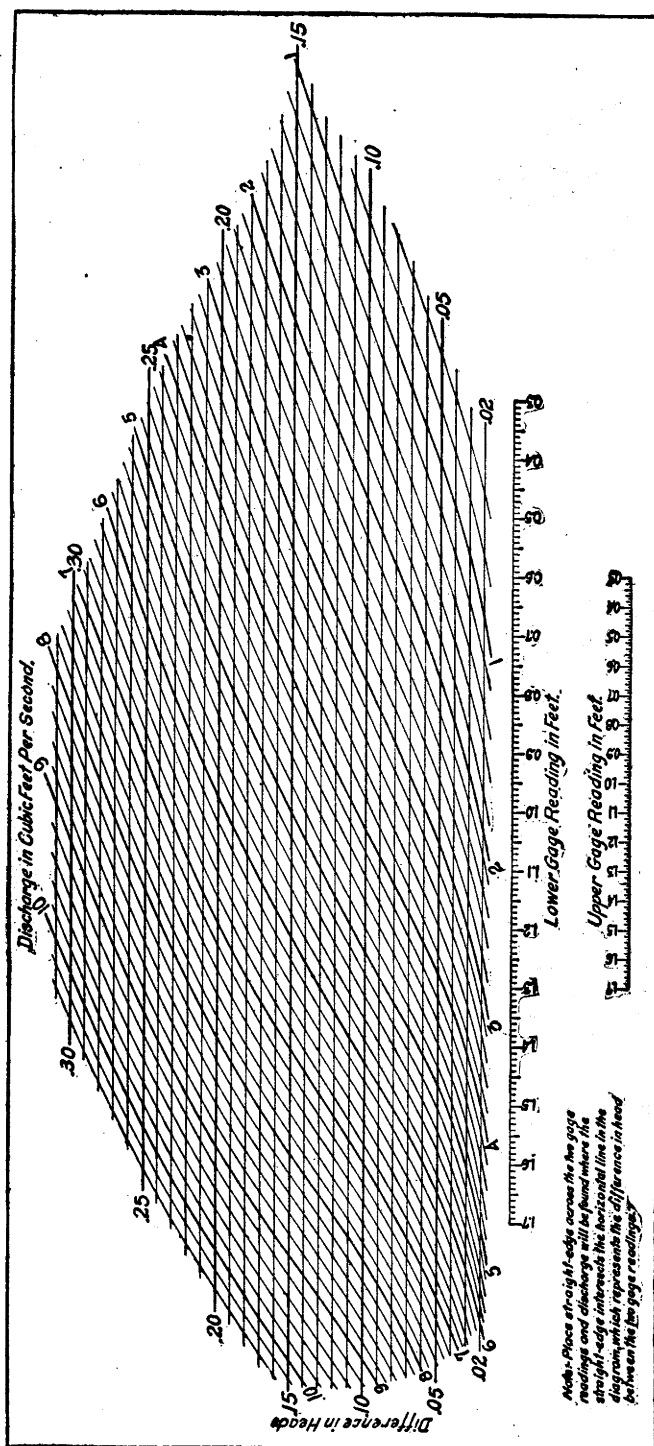


FIG. 12.—Discharge curves for the trapezoidal Venturi flume having 0.5 foot bottom width and side slopes 1 to 1.

CONCLUSION

The Venturi flume is not an exact measuring device, but it is thought to be sufficiently accurate to meet usual practical needs, especially such as are encountered in irrigation practice in the West.

Although experiments have been made only on the smaller sizes of Venturi flumes, it seems reasonable to expect that structures built according to the general plans will be applicable to the measurement of streams of considerable size, with an accuracy compatible with field requirements.

The Venturi flume seems to fulfill the conditions of being free of trouble from sand, silt, or floating trash; requires little loss of head for making the measurement; is a structure that is simple to build, easy to operate, and has a comparatively low cost; and is free from error in measurement due to aquatic growth or other changes in the channel, provided the floor of the flume is not below the grade of the channel.

If the accompanying discharge curves, formulas, or tables are to be used, it is essential that the Venturi flume be built according to the general plans and the gages for measuring the head be placed as shown in the plans. Alterations of the plans or position of gages will necessitate a recalibration for the new arrangement.

A public patent has been applied for which will permit the manufacture or use of this flume by the public without the payment of royalties.

ADDITIONAL COPIES
OF THIS PUBLICATION MAY BE PROCURED FROM
THE SUPERINTENDENT OF DOCUMENTS
GOVERNMENT PRINTING OFFICE
WASHINGTON, D. C.
AT
15 CENTS PER COPY
SUBSCRIPTION PRICE, \$3.00 PER YEAR